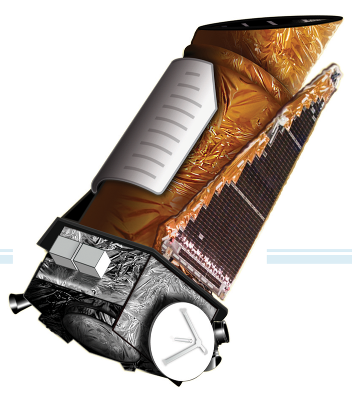
SCIENCE FROM KEPLER COLLATERAL DATA: 50 KSEC/YEAR FROM 13 MILLION STARS ?



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Abstract

As each Kepler frame is read out, light from each star in a CCD column accumulates in successive pixels as they wait for the next row to be read out. This accumulation is the same in the masked rows at the start of the readout and virtual rows at the end of the readout as it is in the science data. A range of these "smear" rows are added together for each long cadence and sent to the ground for calibration purposes. We will introduce and describe this smear collateral data, discuss and demonstrate its potential use for scientific studies exclusive of Kepler calibration,[1,2].

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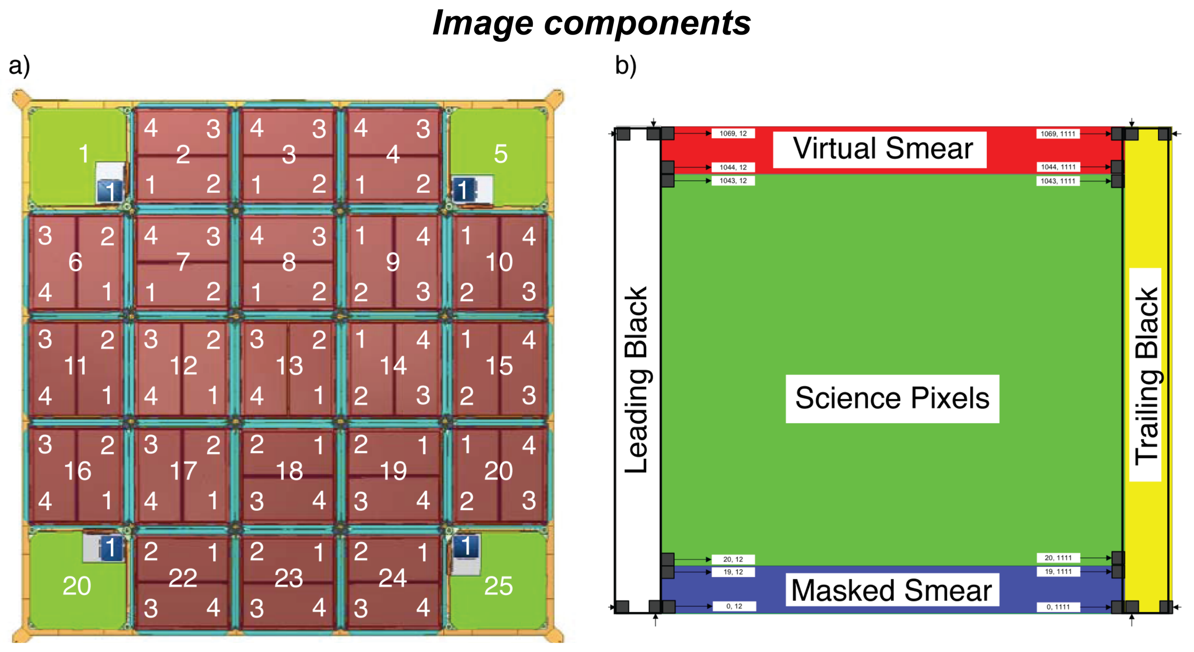
Image components



Terminology

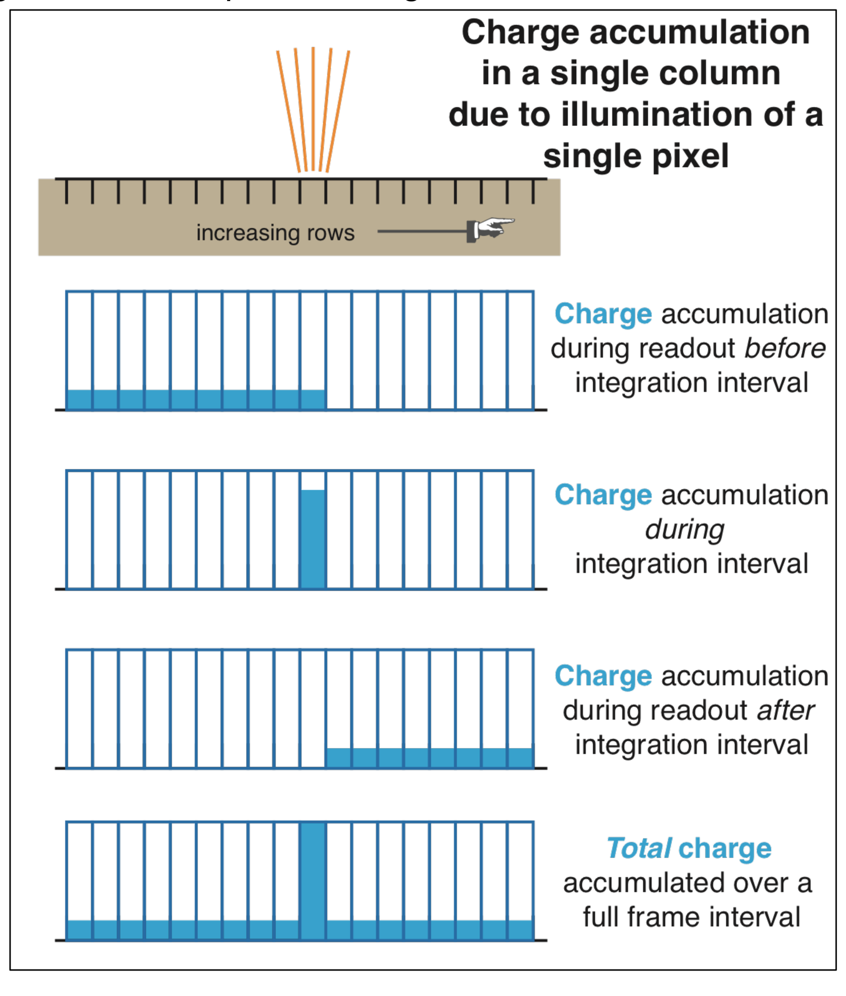
FPA	Entire focal plane array of 21 science modules and 4 fine guidance sensors
Module	Focal plane elements consisting of 2 CCDs or 4 outputs
CCD	Model element consisting of 2 outputs
Output	Basic readout element from which pixels are clocked
Science Pixels	Illuminated real pixels
Masked Smear	Masked real pixel rows preceding each science frame
Virtual Smear	Virtual pixels rows following each science frame
Leading Black	Virtual pixels preceding each science row
Trailing Black	Virtual pixels following each science row

In addition, a parallel transfer interval accompanies each row readout interval. Durations are tabulated below

CCD Charge Collection Sequence: The Kepler Smear Campaign

During Science operations the Kepler focal plane instrument continuously cycles between integration and readout to accumulate frames which are coadded to produce short and long cadences. In the absence of a shutter, light continues to fall on the Kepler focal plane array while the pixels are clocked out during the readout interval. The charge collected in pixels during this time is called *smear*.

The masked rows at the start of the readout contain only this smear plus dark current and the virtual rows at the end of the readout contain only the smear. For calibration, all of the columns of this smear data are collected for 12 masked rows and 12 virtual rows and are coadded over 270 frames for each long cadence. In calibration a scaled version of the smear is subtracted from each target pixel to remove this readout bias. To enable future users to perform calibration, this smear data will be archived in raw form at the MAST.

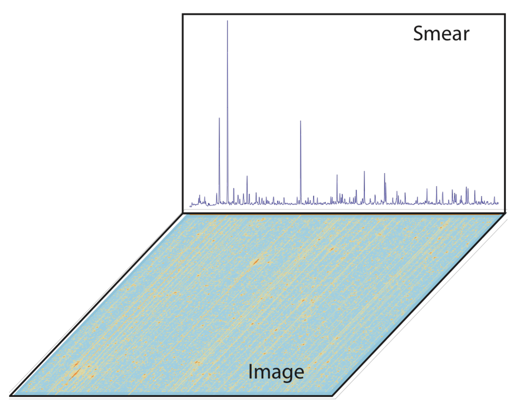


Integration Time for Smear Pixels

Beyond their utility for calibration, smear data represent full field projections from each module output, containing signal from every star in the field, summed over rows. Since Kepler acquires cadence data from only ~6% of science pixels in the target apertures, the only continuous information we have on what's happening in the other 94% of the pixels is from the smear data (full frame images taken several times per quarter provide more complete spatial information). The table below summarizes integration time parameters, and is based on a serial pixel read rate of 3 MHz, 1455 read intervals per row for 1070 rows, and a 58:5 integration-to-readout ratio. The data values acquired are the sum of 12 rows each of masked and virtual smear pixels.

There are 1024 illuminated rows for each output, so the smear pixels are exposed to the diffuse background for a fraction 1024/1070 of the readout period. This combined with the the fact that there are 2 sets of 12 pixel sums, enabling a 24 pixel combined sum for what we are calling a *smear datum* , results in a total diffuse background integration time per datum which is longer than 1 year per year and approximately twice the 2.8×10^7 sec of background exposure received by the science pixels.

The light from a star falls on several pixels across rows and columns and its distribution depends on the subpixel centroid location and spatially varying PRF, however unless a star is near the edge of the science pixel region so that the PRF overlaps the edge, the exposure as defined by effective area × integration time is fixed by the readout period per row. If a star illuminates the telescope with a given flux in photons cm^{-2} sec^{-1}, then the number of photons incident on the focal plane per year is this flux × effective area × the point target integration time listed below. The result is that the smear pixels are accumulating more than 50 ksec /year on each of the 13×10^6 stars in the Kepler field.

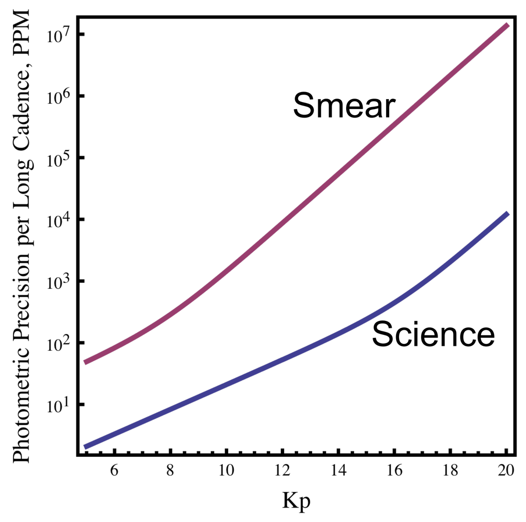


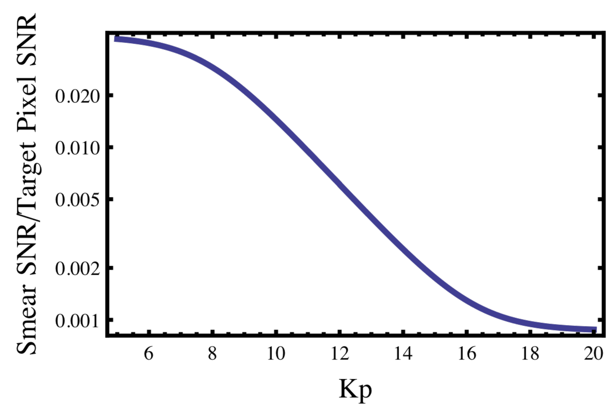
Integration Period Per Frame	6.01982 sec
Readout Period Per Frame	0.51895 sec
Readout Period per Row	0.000485 sec
Smear Pixel Integration Period Per Frame	0.49664 sec
Smear Pixel Integration Period Per Row	0.000485 sec
Number of Smear Pixels Collected	24
Smear Datum Diffuse Background Integration Time per Year (95% observing efficiency)	**5.46×10^7 sec**
Smear Datum Point Target Integration Time per Year (95% observing efficiency)	**53400 sec**

BUT, ... Noise in Smear Pixels

Components of the variance of smear data are summarized in the table below along with signal-to-noise ratio for stars of several Kp values. Plots show the photometric precision on 1 long-cadence time scales as a function of Kp for the smear data in comparison to science pixels assuming typical aperture sizes for the science pixels and the ratio of smear data SNR to science data SNR. For bright stars, shot noise dominates and the ratio is the square root of the ratio of integration times, sqrt(1/517)=1/23. However for Kp>9, read noise begins to dominate and the photometric precision cuts off sharply. Thus the utility of the smear data for monitoring short term variation in most stars is limited.

Kp	12	10	8	6
Signal	2.5×10^3	1.6×10^4	1.1×10^5	6.5×10^5
Shot Noise	50	128	323	809
Dark Current	13			
Background	28			
Read Noise	370			
Photometric precision per long cadence for smear data, PPM	**9000**	**1400**	**285**	**82**
Signal for science targets	1.3×10^6	8.5×10^6	5.4×10^7	3.4×10^8
Photometric precision per long cadence for science targets, PPM	**54**	**21**	**8.3**	**3.3**





Unobserved Bright Stars on Science Pixels

A comparison of on-silicon stars in the KIC to the number observed sometime over Q1-Q9 indicates there are a significant number of very bright stars that have never been observed by Kepler. There are 323 such stars with Kp<10.

Kp	In KiC on Si	# Observed	# Smear Only
<5	1	0	1
5<Kp<6	13	5	8
6<Kp<7	66	37	29
7<Kp<8	145	101	44
8<Kp<9	509	139	70
9<Kp<10	1496	1325	171

Calibration and Data Conditioning

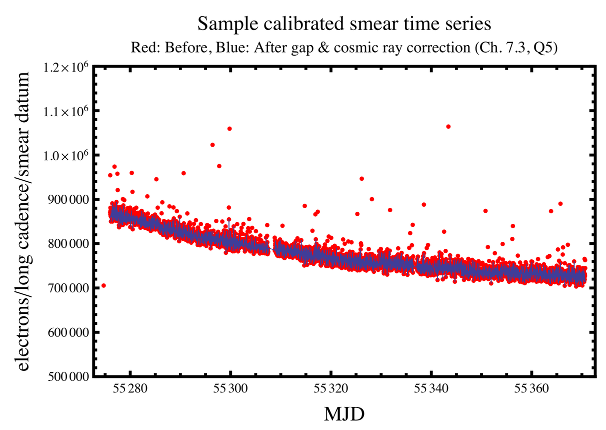
The smear data requires calibration steps paralleling target data [1-4].

- Black Level Correction
- Gain (DN to Electrons)
- Dark Current
- Gaps and Cosmic Rays (see Plot)

Correcting for other systematics errors

- Motion
- Focus changes
- Differential velocity aberration

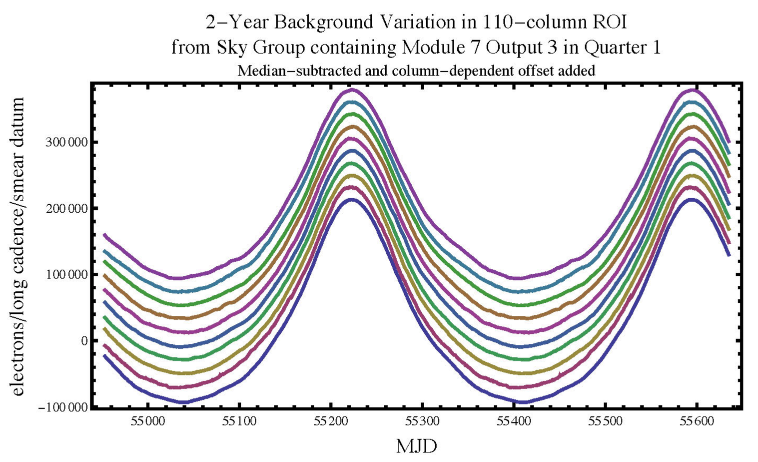
Methods are described in references.



Background

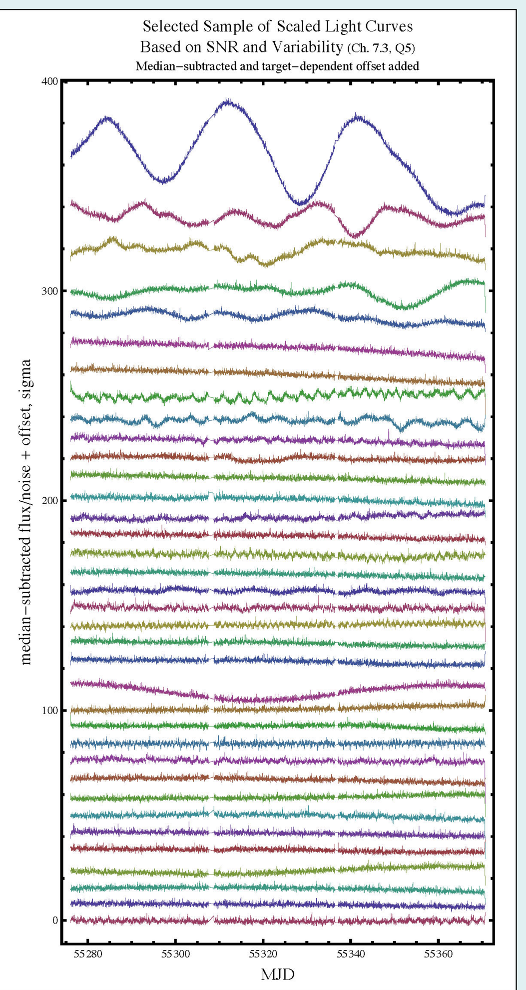
A background variation is estimated using smear data time series by fitting to a series of 6 harmonics of the orbital year (371.63 days) and a step offset for each quarter.

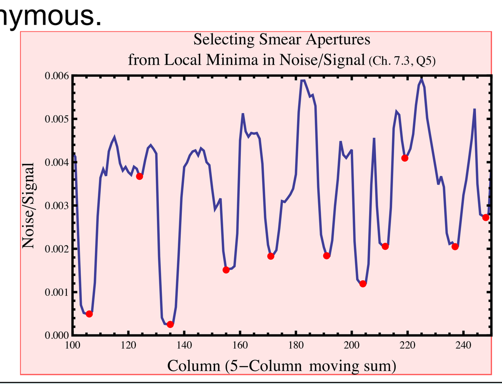
The plot at right shows 110 column medians across the output after removing the steps. The offset is not well determined because of stars in every column.



Light Curves

For illustrative purposes we extract some of the more interesting light curves from a single mod.out and quarter. The steps were to perform a n-point moving sum across the columns, then locate the minima in the photometric precision (see below). We then analyzed the power spectrum of each minimum, by taking an fft of the time series, ordering fft bins by fractional power/bin and then counting the number of bins required to accumulate 50% of the power. Time series with lower values for this *half-power bin count* typically are more interesting, as is evident from the plot at right, which is ordered from top to bottom according to this parameter, and is unlabeled to remain anonymous.





Summary

The raw smear data will be included in the set of archived *Kepler* data. Because of the unique continuously observing nature of the *Kepler* mission it is possible that, even with its limitations, the smear data could be mined for its scientific value. A list of benefits and limitations includes:

•Benefits:

- Continuity of data.
- The only data available for some targets.
- Potential for adding to occasionally observed target data sets.
- Good background sensitivity may be useful for study of diffuse sources.
- More complete data from bright stars that saturate off the top or bottom of an image (using smear data from opposite end).

•Limitations:

- Read noise limits photometric precision for Kp>10.
- Only raw data will be available, so calibration and other preparation steps are required.
- Projected columns may include multiple interesting stars. (but target data could be used to reduce confusion)

References

[1] Jenkins, J.M., et al., "Overview of the *Kepler* Science Processing Pipeline," ApJL, 713 (2), L87-L91 (2010).

[2] Caldwell, D. A., et al., "Instrument Performance in *Kepler*'s First Months," ApJL, *713*, L92-L96. (2010).

[3] Kolodziejczak, J. J., et al., "Flagging and Correction of Pattern Noise in the Kepler Focal Plane Array," *Proc. SPIE*, 7742, 38 (2010).

[4] Kepler Science Handbook and Release Notes.